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THESIS

VISUAL DETECTION OF AIRCRAFT

IN

MID-AIR COLLISION SITUATIONS

Edward Arthur Short

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by

Edward Arthur Short

Lieutenant Commander, United States Navy

Submitted in partial fulfillment of
the requirement for the degree of

MASTER OF SCIENCE

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Approved:

Academic Dean

ABSTRACT

When two aircraft are physically oriented so that continuation on their individual flight plans will result in collision, the final decision of the pilots to take avoiding action is most often based upon visual detection of the other aircraft. Considerable laboratory experimentation has been conducted and reported on the various aspects of visual detection as has much been written about the general theory of computing visual detection probabilities. This thesis is concerned with correlation of a portion of these laboratory results with detection theory into an analytical model for the computation of range at which an aircraft will be detected with a given probability fo. a stated set of meteorological conditions. The theoretical model is first developed for the case of a lookout or observer riding in the aircraft with no other duties than to perform visual searching. Consideration is then given to the case of the pilot who must distribute his available time between visual searching and in-cockpit operation of his aircraft.

The writer wishes to express his appreciation to Mr. Robert G. Richards of the Operations Research Section, Aerojet-General Corporation, Azusa, California, for his guidance in the formulation of the problem and to Professors W. P. Cunningham and S. H. Kalmbach of the U. S. Naval Postgraduate School for their guidance and encouragement while acting as faculty advisors.

SUMMARY

This thesis is concerned with the development of a computational method for determining the probability of visual detection in situations which would result in a mid-air collision between two aircraft. The results of laboratory investigations in the fields of atmospheric conditions, contrast, and human eye detection lobe patterns and detection procedures are related to the physical situation under which a collision may occur. The model is developed initially for the case of a lookout who is riding in the search aircraft and who can devote all of his time to visual search. The discussion is then extended to the case of the pilot of the aircraft who must distribute his time between visual search and operation of his aircraft. A comparative numerical example of the procedure is given and a discussion of the controlling parameters is included.

The initial conditions upon which the probability of visual detection as a function of range equations are based are that the aircraft are operating during daylight conditions in routine level flight and that atmospheric conditions are such that a uniform background of horizon sky is present. The individual who is conducting the search is considered to distribute his glimpses over the area which he is searching in a uniform manner.

Three factors emerge as dominant influences in the determination of the range at which a target will be detected with a given probability; relative closing velocity of the target, time spent looking at a given spot within the search field, and the size of the area being searched. Material improvement can be made in the detection range with the use of electronic devices which alert the pilot to the presence and general location of the target and thus reduce the size of the area to be visually searched.

Programming of the computational procedure for a digital computer will be of significant assistance in permitting a sensitivity analysis of the wide range of possible values for the input meters. Such a program would be of further assistance in evaluating the effect of changes in glimpse distribution over the search field and of changes in the distribution of pilot time between visual searching and aircraft operation.

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LIST OF ILLUSTRATIONS

TABLE OF SYMBOLS

C	-Contrast
B	-Luminance (brightness)
B_o	-Luminance of Object Close at Hand
B_o'	-Luminance of Background Close at Hand
B_R	-Luminance of Object at Range R
B_R'	-Luminance of Background at Range R
R	-Range or Distance
σ	-Extinction Coefficient of the Atmosphere
v	-Meteorological Range
C_o	-Inherent Contrast
C_R	-Apparent Contrast
θ	-Angular Distance off Center of Fixation
α_ℓ	-Threshold Target Diameter
R_m	-Maximum Theoretical Detection Range
Θ	-Azimuthal Angle of Travel of Visual Axis
Φ	-Elevation Angle of Travel of Visual Axis
T	-Length of Time of One Glimpse
S_s	-Velocity of Search Aircraft
S_t	-Velocity of Target Aircraft
A_f	-Frontal Area of Target
A_s	-Side Area of Target
A	-Apparent Target Area
α_t	-Equivelent Circular Diameter of Actual Target
β	-Aspect Angle of Target
G	-Probability of Detection in One Glimpse
V	-Relative Closing Velocity of Target and Search Aircraft
$P_o(R)$	-Cumulative Probability of Detection by an Alerted Observer

TABLE OF SYMBOLS (Cont.)

Ω	-Azimuthal Angle of Field of View to Left and Right of Aircraft Heading
Ψ	- Azimuthal Scan Angle
k	-Number of Sub-sectors into which the Field of View is divided
γ	-Elapsed Time During a Search Cycle
m	-Number of Glimpse Sequences During a Search Cycle
t	-Time Devoted to Aircraft Operation During a Search Cycle
$P_p(R)$	-Cumulative Probability of Detection by an Unalerted Pilot

CHAPTER I

INTRODUCTION

During the past fifteen years, there has been enormous growth in the numbers of civilian and military aircraft which are using our airspace every hour of every day. Over-crowding within allotted airspace has become a vital concern of many private and public organizations and investigations of means to eliminate and/or control these conditions are a continuing program.

The increase in aircraft population has caused not only a burden on existing facilities, but has created or amplified many problems in the area of flight safety. One such problem has been the increase in the number of mid-air collisions.

During recent years a number of devices have been proposed and developed which in one manner or another attempt to alert the pilot of an aircraft to the existence of a possible collision situation. Under conditions of reasonable visibility, the final evasive action to avoid collision is still most often based upon a visual detection of the other aircraft.

The conditions which affect the probability of visual detection can be roughly divided into four major areas: meteorological conditions; visibility of targets; physiology of the human eye; geometry of the visual search situation. Considerable experimentation and investigation has been accomplished in each of these areas.

This thesis addresses itself to the task of assimilating some of the results in these areas into a mathematical model for computing the probability of visual detection of an aircraft on or near a collision course with another aircraft under daylight conditions.

To accomplish this task, the model is first developed for the simplified case in which an observer is riding in the aircraft with no duties to perform other than to search for the intruder aircraft. The observer is alerted to the general location and time at which this intruder will appear.

The model is then extended to a consideration of the pilot of the aircraft who has no prior knowledge of the existence of a potential collision situation. The pilot is carrying out his regular visual search in addition to the duties directly connected with the operation of his aircraft.

Finally, a numerical example of the calculations is presented in Appendix II for an assumed set of flight conditions and the resulting detection curves are computed.

CHAPTER II

FACTORS AFFECTING VISUAL DETECTION

A. Contrast

The visibility, or probability of detection, of distant objects has been extensively studied under both laboratory and field conditions. The maximum limit of range at which an object will be visible can be predicted from data concerning the contrast threshold for the human eye if proper allowance is made for the reduction in this contrast caused by the atmosphere.

Contrast or difference in luminance or chromaticity is the means upon which most of the information about our world which we obtain through our sense of vision depends. An object is recognized because it has a different color or brightness from its surroundings, and also because of the variations of brightness or color over its surface. The shapes of things are recognized by the observation of such variations. In problems involving vision through the atmosphere, contrast in luminance is much more important than contrast in chromaticity.

As presented by W. E. K. Middleton (1), contrast due to luminance is defined in terms of an isolated object surrounded by a uniform and fairly extensive background. If the luminance of the object is B and that of the background B', the contrast is defined by the equation

$$C = \frac{B - B'}{B'} \qquad 2.1$$

if the object is less luminous than its background, the contrast is negative, reaching -1 for an ideal black object; if the object is brighter than the background, C may take on any positive value. Very large values of C arise for extremely bright lights at night. In the daytime contrasts

greater than 10 seldom occur and are more usually in the range 0 to 5.

S. Q. Duntley (2) studied the area of contrast reduction due to the atmosphere and found that the contrast between pairs of objects adjacent in the field of view varies exponentially with distance from the observer. Let the two objects (or an object and its background) have luminances B_o and B'_o respectively when seen close at hand, B_R and B'_R when seen from a distance R. Then for the observation of a target and its background in the horizontal (or near horizontal) plane of the observer

$$B_R - B'_R = (B_o - B'_o)e^{-\sigma R} \tag{2.2}$$

where σ is the extinction coefficient which reflects the amount of reduction in luminance due to the atmosphere. It was further found that under conditions of observation of an object against a uniform background sky

$$\sigma = 3.912/v \tag{2.3}$$

v is defined as the meteorological range or that distance for which the transmission contrast for the atmosphere is two percent. In practical situations, meteorological range is that item of weather data referred to as visibility.

Adopting the definition of 2.1, we may call

$$C_o = \frac{B_o - B'_o}{B'_o}$$

the inherent contrast, and

$$C_R = \frac{B_R - B'_R}{B'_R}$$

the apparent contrast. Combining these results with 2.2 and 2.3, we have:

$$C_R = C_o \,(B'_o/B'_R)\, e^{-3.912\ R/v}$$

Under the previous stipulation of the observation of an object against a uniform background of horizon sky, $B'_o = B'_R$, and

$$C_R = C_o e^{-3.912\ R/v} \qquad 2.4$$

as a specialized expression from which it is possible to compute the apparent contrast of an object and its background at various ranges for a given inherent contrast and meteorological range corresponding to those conditions.

B. Apparent Contrast Versus Stimulus Area

In 1946 H. R. Blackwell (3) reported the results of an extensive series of experiments conducted in the laboratory to determine the mutual relation between background luminance, stimulus area, and apparent contrast. Stimuli, circular in form and brighter than the observation screen, were presented in any of eight possible positions on the screen for an exposure of six seconds. As a consequence, the observers scanned the screen at a rate comparable to that employed by lookouts in the military service in determining the position they thought the stimulus occupied.

Background luminance was varied from zero to 1000 foot-lamberts. The latter value corresponding to full daylight. Circular stimuli varied in diameter from 0.6 to 360.0 minutes of arc. For a particular stimulus size and background luminance it was possible to determine the threshold apparent contrast which was discernable by the observers. Threshold apparent contrast is defined as that minimum apparent contrast for which 50% detections occur after due allowance has been made for chance successes. Over 220,000 observations were made to validate the data obtained.

A series of smoothed data curves were compiled of log[1] stimulus diameter in minutes of arc versus log threshold apparent contrast for each specified condition of background luminance. Figure 1 reproduces a portion of the curve for the case of 1000 foot-lamberts of background luminance (the daylight case considered in this thesis). The reader is referred to referance (3) for the complete family of curves.

It is conversely true that if apparent contrast is determined in some manner such as computation using equation 2.4 for a given range the corresponding diameter of the minimum size circular target (stimulus) which is theoretically detectable at that range may be determined from figure 1.

1. The term log used throughout this paper denotes logarithm to the base 10 while LN denotes the natural or naperian logarithm.

THRESHOLD TARGET DIAMETERS VS. CONTRAST

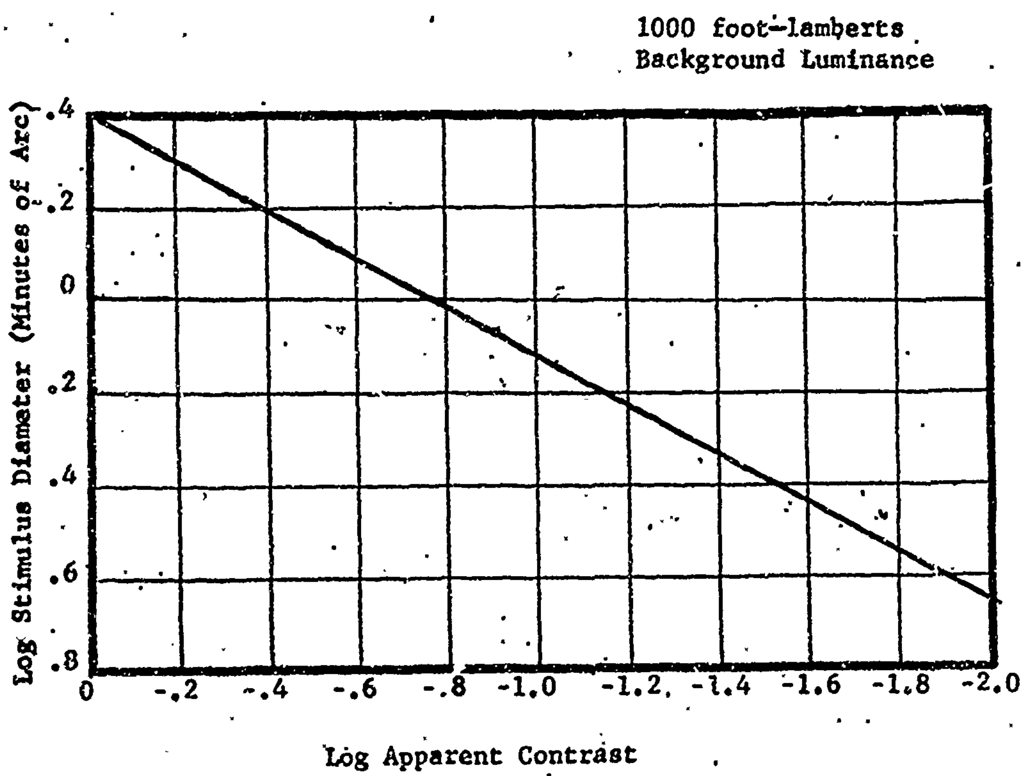


Figure 1

C. Visual Detection Lobe of the Human Eye

In general construction, the eye is very similar to a camera. The transparent front surface or cornea and the crystalline lens together constitute a compound lens which forms on the retina, at the back wall of the eye, an image of any given object in front of the eye. Between the cornea and the crystalline lens there is a small aperture known as the pupil. This aperature is variable in size over a limited range and determines the quantity of light which enters the eye.

The retina corresponds to the sensitized plate or film in the camera. It contains two different types of sensitive elements known as rods and cones. The rods serve for night vision and are incapable of distinguishing color. The cones are responsible for vision in daylight and for all color vision. The central part of the retina, through which the visual axis passes, is known as the fovea. This visual axis makes a small angle with the optic axis of the compound lens system. The diameter of the fovea subtends an angle of between one and two degrees at the effective center of the lens. The fovea which contains only cones is the region of most distinct daylight vision. As the angular distance from the axis increases beyond the edge of the fovea, the parafoveal region is entered and the number of cones in a unit area decreases, at first rapidly and then more slowly while the number of rods in a unit area gradually increases out to about 18 degrees and then decreases. In daylight, therefore, a given target can be most easily seen by looking straight at it while at night a better view is obtained by looking about six degrees off the most direct line of sight.

Unlike radar which scans continuously, the eye moves in jumps while searching and is capable of vision only during period of little or no motion. These periods are known as fixations. In a given fixation or group of fixations, a target at extreme range can be seen in daylight only on the fovea

so that the visual axis must be well within one degree of the line joining the target and the eye. As the range decreases, regions in the parafoveal area become capable of detecting the target, at first those near the fovea and then those farther out. Hence targets at less than extreme range can be seen not only on the fovea but off the fovea as well.

The size of the target and its range combine to determine the solid angle which the target subtends at the eye and hence the size of the image on the retina. The three characteristics of the target and its background upon which the discrimination of the eye depends under daylight illumination are:

1. Contrast of the target against its background.
2. Solid angle subtended by the target.
3. Shape of the target.

The starting point for the mathematical definition of the detection lobe is an empirical relation derived from optical experiments cited and discussed in reference (4). From these experiments with circular targets it was found that apparent contrast C_R can be represented as a function of the solid angle ω subtended by the target at the eye, by the following equation:

$$C_R = a + \frac{b}{\omega}$$

where a and b are constants for any one retinal region. Instead of using solid angle ω, it is more convenient to employ α, the angle subtended at the eye by the diameter of the equivalent circular target. The quantities a and b have different values at different angular distances from the center of the fovea. If θ is this angular distance in degrees, from center

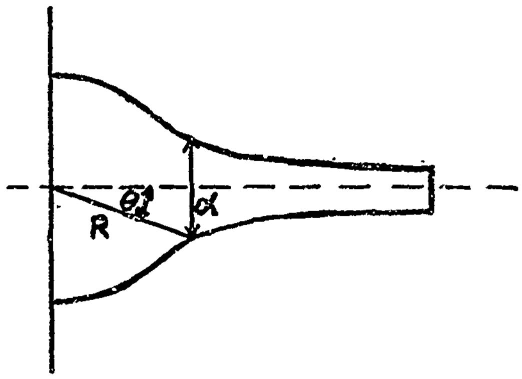
of the equivalent circle to the center of the fovea; α, the visual angle in minutes of arc; and C_R the threshold apparent contrast in percent, the experimental data can be represented by:

$$C_R = 1.75\theta^{1/2} + \frac{19\theta}{\alpha^2} \qquad 2.5$$

the angle θ in this equation ranges from 0.8 degrees to about 90 degrees. For values less than 0.8 degrees, C_R is constant and equal to the value at $\theta = 0.8$.

As previously discussed in Section A of this chapter, apparent contrast is a function of target range for a given inherent contrast and meteorological range. Employing equation 2.4, the left hand member of 2.5 may be computed. This value of C_R may then be used to enter Figure 1 to find the corresponding threshold circular target diameter, α. Thus having fixed the values of target range, R, and target size, α, equation 2.5 may be solved for the corresponding value of θ, the angular distance off the fovea. The limiting value of θ is considered to be 90 degrees off the axis. The maximum possible value of target range is designated R_m and is defined as the maximum range at which the target can be detected based upon meteorological range and inherent contrast. A series of nomograms have been developed (2) which make it possible to find the value of R_m directly for a stated meteorological range and inherent contrast.

The threshold detection lobe pattern of the eye is determined by solving equation 2.5 for θ, $0 \leq \theta \leq 90°$, over the range of values of target range and target size. The results are represented graphically as a polar plot of θ versus R or α for a section through a typical detection volume.



The surface of revolution described by this curve is called the lobe pattern or simply the detection lobe. It can be thought of as attached to the eye and moving with it. Any target which falls within the lobe during a fixation will be seen and any target which falls outside will be missed. Actually, the boundry of the detection lobe is not as sharp as the diagram would indicate. Some targets just inside the boundary may be missed while others just outside may be seen. However, since the boundry can be so defined that these two effects compensate one for the other, it can be assumed with some assurance that the results will be the same as though the transition region had been considered in detail.

D. Geometry of Visual Search

While searching a visual field, the human eye does not scan continuously, but moves in jumps and can see only during the pauses or fixations between jumps. The minimum fixation time for the eye to detect an object is approximately .25 seconds. In general, six to eight fixations are required to establish a definition of the target. This means that for proper and thorough searching, the eye should be fixed on a given area for from 1.5 to 2 seconds before shifting to another area. Under certain conditions, it is possible to reduce the number of fixations required without seriously affecting the efficiency of the search. An example of such a condition would be one in which the target was of considerable size and of high inherent contrast. In general, though, when one is searching for small objects which are difficult to distinguish from their background, it is best to employ the range of six to eight fixations. The associated period of from 1.5 to 2 seconds is defined as one glimpse.

Consider the specialized case in which the two aircraft involved in a collision situation are exactly at the same altitude i.e., the two dimensional situation. The search aircraft is located at the origin of coordinates and the intruder aircraft is located, at any given instant of time, on a range arc relative to this origin. If the visual detection lobe of the searcher in the aircraft at the origin is superimposed on the relative position of the two aircraft, the resulting geometry is illustrated in Figure 2, where the angular travel of the visual axis during scanning in azimuth is limited to an angle θ. This limitation in the size of the azimuthal angle may be imposed by the following considerations:

1. The physical restrictions imposed by the configuration of the aircraft cockpit.

2. Prior intelligence of the expected position from which the intruder would appear.

3. Division of the azimuthal arc into sectors of search responsibility when more than one observer is present.

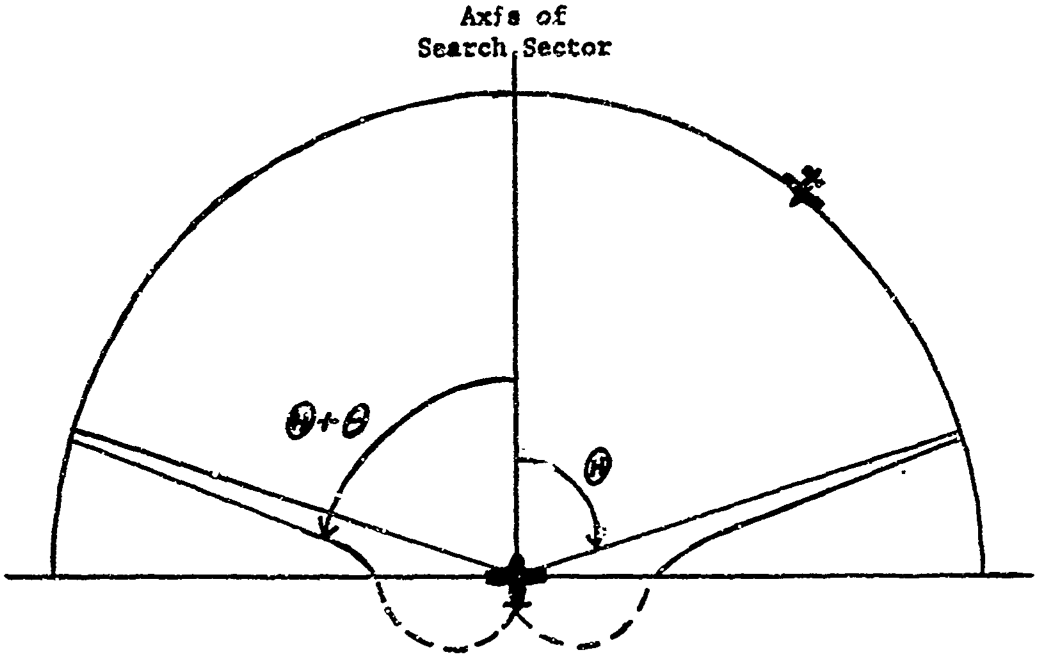


Figure 2

If the restriction that the two aircraft be at the same altitude is now removed, search in elevation as well as azimuth must be considered. Let Φ be the angle above and below the horizon of the search, the scan in elevation is shown in Figure 3.

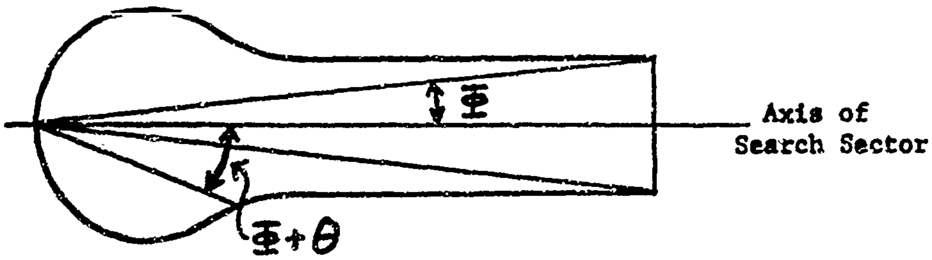


Figure 3

The area under search is therefore a solid angle with the dimensions of $2\Theta + 2\theta$ in azimuth and $2\Phi + 2\theta$ in elevation.

Some system must be adopted for searching the given solid angle in order to assure that the number of glimpses in any given direction will be the same, per unit of time, for any direction within the given solid angle. This scanning system must satisfy two requirements: the time required to complete one scan must be small compared to the total search time; and, the distribution of glimpses should be reasonably uniform over the solid angle scanned. E. S. Krendel and Jerome Wodinsky reported (5) the results of their statistical analysis of a series of visual detection experiments conducted at the Air Force Cambridge Research Laboratories. Their conclusions were that the general adequacy of an exponential distribution to describe visual search had been demonstrated subject to the following conditions:

1. The interval of time over which search takes place should be small and limited to about 30 seconds.
2. The defining constraints of contrast, target size, search field, and background luminance must remain fixed over period from the commencement of the search until detection is achieved.
3. The observer should not follow a consistent pattern while searching.

Within the framework of this chapter and the restrictions of the preceeding paragraph, the development and discussion of the detection model will be carried out in subsequent chapters.

CHAPTER III

DETECTION BY AN ALERTED OBSERVER

In the development of the visual detection model it is desirable to first consider the simplified case of an observer riding in the search aircraft. This observer has no duties connected with the operation of the aircraft other than to search for the intruder or target aircraft. It will be assumed that this observer has prior knowledge of the general location where and time at which the target will appear. Such advanced information would be accomplished in a laboratory situation by the design of the experiment or under operational conditions by intelligence information, warning from a ground control station, or radar or some other type of proximity device installed in the search aircraft.

The previously stated or implied assumptions upon which the probability of detection model are based are as follows:

1. The defining constraints of inherent contrast, actual target size, search field, and background luminance are constants over the period from the commencement of the search until detection is achieved.
2. The distribution of glimpses over the solid angle scanned is considered to be uniform.
3. The detection is taking place under daylight conditions of uniform sky illumination.
4. The sun's directional effect is ignored.
5. The courses and speeds of the search and target aircraft are such that their relative motion will ultimately result in an actual or near collision situation.
6. The observer is giving optimum performance while searching and

his eyes are considered "normal", i.e., having no physiological defects.

To set up the conditions for the computation of the probability of detection, the following inputs are required:

1. Inherent contrast - C_o
2. Meteorological range -v
3. Maximum range at which a target can be detected based upon meteorological range and inherent contrast. -R_m
4. Azimuthal angle - Θ, and elevation angle - Φ, of the search sector.
5. Length of time of one glimpse in seconds - T.
6. Velocity of the search aircraft - S_s, and of the target aircraft - S_t.
7. Frontal area - A_f, and side area - A_s of the target.

With the values of inherent contrast and meteorological range, the values of apparent contrast are computed at convenient range intervals from R_m to zero. From the equation

$$C_R = C_o e^{-3.912 R/v} \qquad 2.4$$

Figure 1 is entered with these results to determine the corresponding values of threshold target diameter, α_ℓ.

For each triplicate of values (R, C_R, α_ℓ), a value of the angular distance in degrees from the threshold target center to the center of the fovea, θ, may be computed from:

$$C_R = 1.75\theta^{1/2} + \frac{19\,\theta}{\alpha_\ell^2} \qquad 2.5$$

in this manner the values of θ are found for $0 \leq \theta \leq 90°$. The resulting

threshold detection lobe may be represented conveniently by either a polar plot or a rectangular plot. Since the detection lobe is symmetrical about its foveal axis, it is sufficient to plot only one half of the lobe. Figure 4 is a rectangular plot of a representative detection lobe. The abscissa is plotted in values of visual angle off the center of fixation, θ. The ordinate values are the dimensionless quantity of relative threshold target diameter, based upon α_{ℓ} at R_m. Figure 4, therefore, represents the theoretical detection lobe pattern of the observer for a selected set of meteorological and contrast conditions. If the equivelent circular diameter of an actual target α_t, is compared with the threshold target diameter, α_{ℓ} at a given range, the ratio α_{ℓ}/α_t may be used to enter the ordinate of figure 4 to determine the corresponding angle off the visual axis at which this actual target will be detected. If the ratio is greater than 1 the target will not be detected. The equivelent diameter of a circular target in minutes of arc may be determined from the relation:

$$\alpha_t = 1293\, A^{1/2}/R \qquad 3.1$$

where A is the apparent area of the target in square feet and R is the range to the target in yards.

VISUAL DETECTION LOBE

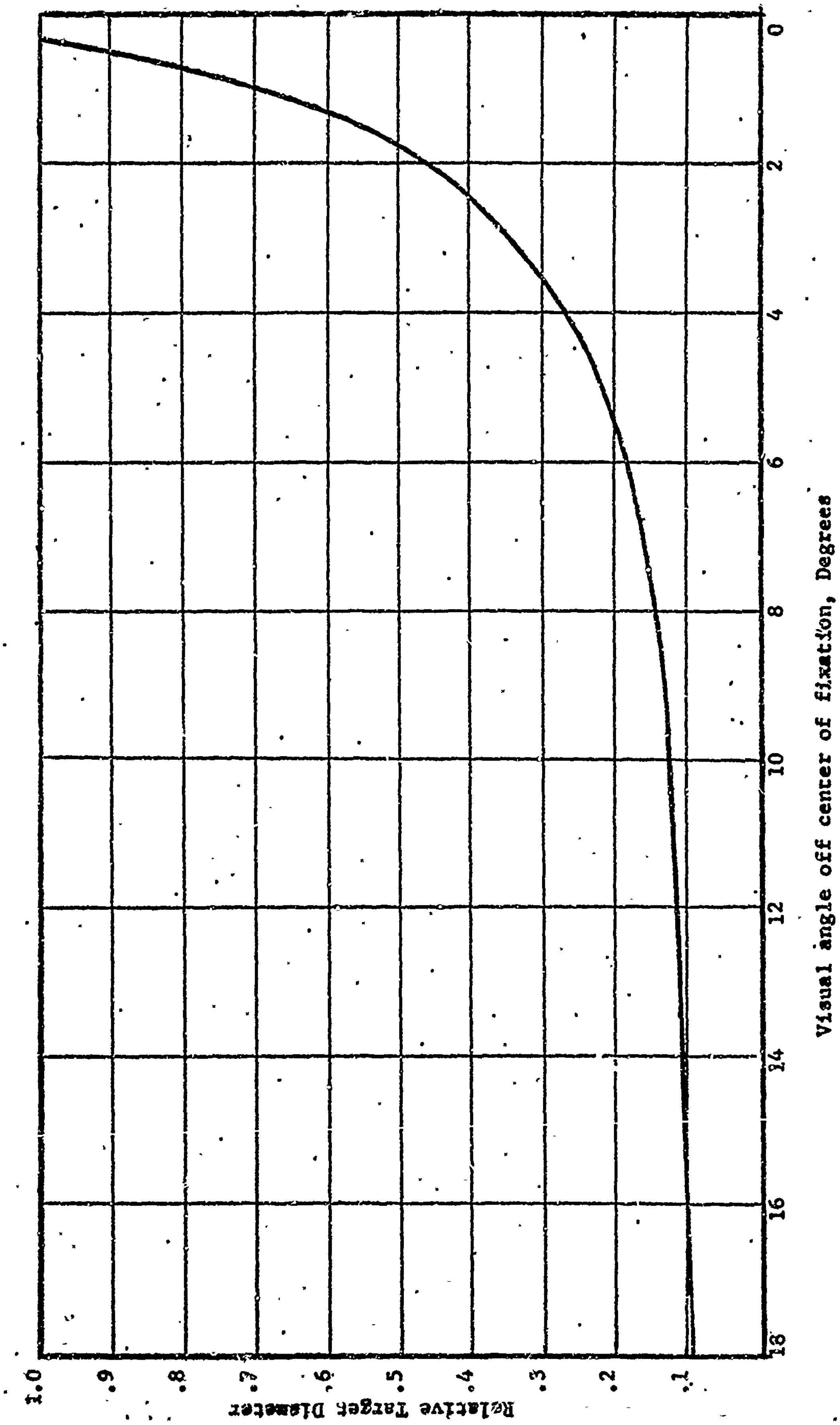


Figure 4

The area of the target which is presented to the observer will vary with the angle at which the target is approaching the search aircraft. This observable area is designated as A, the apparent area of the target. The apparent area of the target is related to its actual frontal area, A_f, and its side area, A_s, through the aspect angle of the target. Aspect angle is defined as the angle between the target heading and the observer's line of sight to the target. Apparent target area is computed from:

$$A = A_f \cos\beta + A_s \sin\beta \qquad 3.2$$

where β is the aspect angle and is shown in the figure below.

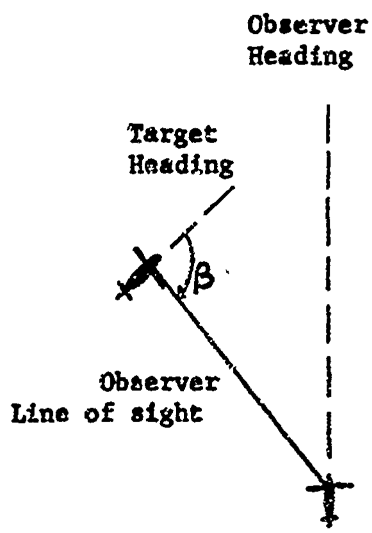


Figure 5

Given the speeds of the search and target aircraft under a collision situation, the arc of possible positions relative to the heading of the search aircraft from which the target aircraft must appear can be found. For any particular bearing within this arc the aspect angle and relative speed of closure of the two aircraft may be determined. These determinations are most conveniently made by solution of the relative motion triangle using the standard U. S. Navy Maneuvering Board.

An analytical discussion of the solution of relative motion problems is given in Chapter 1 of reference 4.

The bearing for which the aspect angle and relative speed of closure was found is designated as the axis of the search sector shown in figures 2 and 3. Since the observer is alerted to the general position from which the target will appear, he will confine his search to an angle $\Theta + \theta$ to the left and right of the axis and $\Phi + \theta$ above and below this axis.

E. S. Lamar (6) has developed a relationship based upon glimpse probability by which the cumulative probability of detection of a target may be determined. In any given glimpse, the chance of detecting the target is the chance that the target is within the detection lobe. Since this lobe may be pointed in any direction within the solid angle of the search sector, this chance is simply the ratio of the solid angle of the detection lobe to the solid angle of the search sector. This chance or probability is designated G, the glimpse probability, and is given by:

$$G = \theta^2/(\Theta+\theta)(\Phi+\theta) \qquad 3.3$$

Assume that each glimpse is an independent event. Then the probabilities of detection for the various glimpses multiply in accordance with the usual laws for independent probabilities, i.e., the failure probabilities multiply. Indexing the G's successively, the probability of detecting the target by the time it reaches range R (it should be recalled that in collision situations the target closes on a constant bearing and therefore detection probability is a function of range only) is:

$$P_o(R) = 1 - \prod_{i=1}^{n} (1 - G_i) \qquad 3.4$$

$\prod_{i=1}^{n}(1 - G_i)$ is the product of terms of the form $(1 - G)$ for all integral values of i from 1 to n corresponding to the number of glimpses.

Equation 3.4 is difficult to work with in its present form, but may be transformed to the more useable logarithmic form

$$P_o(R) = 1 - \mathrm{EXP}\left[\sum_{i=1}^{n} \mathrm{LN}\,(1 - G_i)\right] \qquad 3.5$$

G_i is a function of R since θ on which it depends is a function of R. If G_1 is taken at maximum detectable range R_m, G_1 is a function of R_m. Let Δ be the relative distance traveled between glimpses, then G_2 is a function of $R_m - \Delta$; G_3 A function of $R_m - 2\Delta$, etc.

The first glimpse after the target reaches the maximum detectable range may occur when the target is anywhere between R_m and $R_m - \Delta$. Hence, for the G_1 term the average value of LN $(1 - G_1)$ over the interval between R_m and $R_m - \Delta$ is needed

$$\mathrm{LN}\,(1 - G_1) = 1/\Delta \int_{R_m - \Delta}^{R_m} \mathrm{LN}\,(1 - G_1)\,dR \qquad 3.6$$

Taking similar terms for the successive G's and summing as indicated in equation 3.5, it is found that each integral is of the same form and that the lower limit of one corresponds to the upper limit of the subsequent one. The whole series summation, therefore, can be replaced by a single integral with proper limits. Thus,

$$P_o(R) = 1 - \mathrm{EXP}\left[1/\Delta \int_{R}^{R_m} \mathrm{LN}\,(1 - G)\,dR\right] \qquad 3.7$$

Finally, recall that Δ is the distance traveled between glimpses and is thus the product of the glimpse time T and the relative speed of closure of the two aircraft V. Therefore, in final form:

$$P_o(R) = 1 - \text{EXP}\left[1/VT \int_R^{R_m} \text{LN}\,(1 - G)\, dR \right] \qquad 3.8$$

using the above equation is possible to find the probability with which the observer will detect the target at any selected range out to maximum detectable range R_m. It must be remembered that this computation is dependent upon the aspect angle of the target and its relative speed and thus the results obtained are only valid for a target on the bearing from the observer for which these quantities were obtained. If the target was expected from another bearing within the arc of possible collision positions, the procedure of finding aspect angle, relative speed, apparent area, and α_t would again be followed. With the values of α_e / α_t, the corresponding values of θ would be determined from Figure 4. Employing equations 3.3 and 3.8, the probability of detection as a function of range would be found. In a similar manner a family of detection curves may be developed for all possible positions of the target aircraft.

A discussion of the effect of each of the variables of equation 3.8 on the probability of detection is contained in Appendix I.

CHAPTER IV

DETECTION BY THE UNALERTED PILOT

In the normal operating situation for aircraft, lookouts are not available to perform the visual detection function and this responsibility is assigned to the pilot in addition to the duties connected with the operation of the aircraft itself. For multi-engine aircraft having a copilot in the cockpit, visual detection responsibility during routine level flight is assigned to that half of the field of view corresponding to the seat position in the cockpit. The development of the theoretical model will confine itself to consideration of one person in the cockpit. The presence of a copilot is merely a special case of this which reduces the size of the sector in which the pilot must conduct his search.

The pilot who is unaware of a target closing on a collision course will conduct his visual search throughout the entire field of view. This field of view is limited only by the physical restrictions imposed by the configuration of the aircraft cockpit. There is, of course, a natural tendency for an individual to search in a forward direction rather than behind himself during routine level flight. For purposes of discussion it will be assumed that some restriction does exist, either physical or psychological, which causes the field of view to be limited in azimuth to an angle Ω to the left and right of the aircraft heading. Search in elevation will be considered, as before, to be the angle Φ above and below the horizontal plane of the pilot.

The field of view within which the pilot will conduct his search is thus defined by a solid angle with dimensions of $2\,\Omega$ in azimuth and $2\,\Phi + 2\,\theta$ in elevation. The large size of this solid angle leads one to the conclusion that during the process of its search many glimpses will be

taken at various positions within the search field. It will be recalled that the eye is only capable of vision during periods of little or no motion. The general method by which the field of view is covered is to commence at some point within the field with a glimpse and then scan in azimuth and possibly elevation to another point where the next glimpse is taken. The process of glimpse scan glimpse is continued to the boundry of the search field and then conducted in a reverse azimuthal direction to the opposite boundry where, again, azimuthal direction is reversed and the process repeated until the general location of the inital glimpse is reached. This one time coverage of the search field is defined as a glimpse sequence. During a glimpse sequence single glimpses are taken in various portions of the entire search field. It will be again assumed that these single glimpses are uniformily distributed over the solid angle of the field of view.

During the glimpse sequence the time spent scanning between glimpses may be considered as dead time since nothing is contributed to the probability of target detection. The target aircraft, however, continues to close the search aircraft during this dead time and it must therefore be accounted for in computing the distance traveled by the target between glimpses. Glimpse time, T, is redefined as the elapsed time between the commencement of one glimpse and the beginning of the next one and will include the dead time of scanning.

The azimuthal angle traversed in scanning from the position of one glimpse to the next has been studied to some extent under laboratory conditions exploying the electro-oculographic technique (7). This technique takes advantage of the fact that a potential difference exists between the front and back of the eye. Electrodes are placed above and below each eye,

and at the temporal side of each eye. The cornea is positive relative to the back of the eye, so as the cornea approaches or recedes from a given electrode the electric field at the site of that electrode becomes more or less positive accordingly. By means of appropriate DC amplification and recording, it is possible to obtain records of the horizontal and vertical components of the eye movements. The results of the experimentation indicate that scan angle most often takes on a constant value for the distance moved from one glimpse to the next. The field of view used in these experiments was much smaller than that with which the pilot in an aircraft is faced. It is reasonable to conjecture that this azimuthal scan angle, Ψ, will vary proportionately with the size of the field of view but that it will remain constant for any given field. Adopting this convention, the search field of the pilot may be divided into a number of k, of equal sub-sectors as shown in frontal view below:

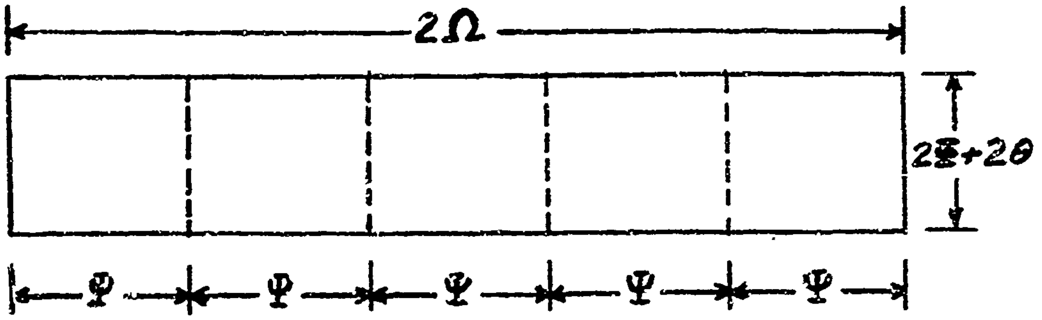


Figure 5

It can be seen that the solid angle of the field of view is thus divided into k equal size solid angles of dimensions Ψ in azimuth and $2\Phi + 2\theta$ in elevation. Considering figure 2, Ψ may be defined as equalling $2\Theta + 2\theta$ at maximum detectable range, R_m. The chance of detection in a single glimpse within any one of these sub-solid angles at any range is as previously shown in equation 3.3.

$$G = \theta^2/(\Theta+\theta)(\Phi+\theta) \qquad 3.3$$

The values of Θ and Φ in the case of the unalerted pilot will generally be larger than those for the observer who is aware of the approximate position from which the target will appear.

Returning to Figure 5, consider a single glimpse sequence occuring over this search field. It can be seen that for all possible positions from which the sequence may start that an average of two glimpses will take place in each sub-sector during that sequence. If several glimpse sequences are taken in succession, then, the total glimpses per subsection will be 2m; m = 1, 2, 3,....according to the number of successive sequences. Assuming that each glimpse is an independent event, the probability of not detecting the target in a series of m successive sequences in any one of the k sub-sectors is:

$$P_p = (1 - G)^{2m} \qquad 4.1$$

The pilot of an aircraft even in routine level flight cannot devote all of his time to visual search. He must spend a portion of this time in the in-cockpit operation of his aircraft; checking the instrument panel; correcting flight attitude; adjusting engine settings; etc. To account for this division of time, a search cycle, τ , is defined as the sum of the time spent in actual visual search and the time devoted to aircraft operation, t. In the case of routine level flight considered here, search cycles occur in succession and are of equal length. The length of a search cycle is given by:

$$\tau = 2mkT + t \qquad 4.2$$

Indexing the G's of equation 4.1 successively, the probability of detecting the target by the time it reaches range R is:

$$P_p(R) = 1 - \prod_{i=1}^{r} (1 - G_i)^{2m} \qquad 4.3$$

$\prod_{i=1}^{r} (1 - G_i)^{2m}$ is the product of terms of the form $(1 - G)^{2m}$ for all integral values of i from 1 to r corresponding to the number of search cycles.

The transformation of 5.3 to the more useable logarithmic form gives:

$$P_p(R) = 1 - \text{EXP} \left[2m \sum_{i=1}^{r} \text{LN}(1 - G_i) \right] \qquad 4.4$$

If the search pattern employed by the pilot is formalized to the extent that he commences the glimpse sequence of successive search cycles in the next adjacent sub-sector to the one in which he completed the previous search cycle, the elapsed time between any two glimpses will be . It is not felt that this is an unrealistic requirement to place upon the model in as much as search cycles times for routine flight are on the order of 30 seconds and in that short time the pilot's orientation in his field of view is not lost.

Let γ be the relative distance traveled between search cycles, then, as previously discussed in Chapter III, G is a function of R_m ; G_2 a function of $R_m - \gamma$; G_3 a function of $R_m - 2\gamma$, etc.

Since each glimpse may occur anywhere in the range interval corresponding to its search cycle, the individual LN (1 - G) are averaged over their intervals as before. Summing these averages as indicated in equation 4.4, it is found that the whole series summation may be replaced by a single integral with proper limits.

$$P_p(R) = 1 - \mathrm{EXP}\left[2m / \gamma \int_{R}^{R_m} \mathrm{LN}\ (1 - G)\ dR \right] \qquad 4.5$$

Lastly, recalling that γ is the distance traveled between search cycles, it may be replaced by the product of relative closing velocity of the two aircraft, V, and the length of time of a search cycle, τ. Therefore, the probability of detection by the unalerted pilot as a function of range may be expressed by the relationship:

$$P_p(R) = 1 - \mathrm{EXP}\left[2m / V\tau \int_{R}^{R_m} \mathrm{LN}\ (1 - G)\ dR \right] \qquad 4.6$$

The similarity of equations 3.8 and 4.6 is obvious from the like manner in which these relations were developed. It is readily apparent that, in general, the range at which the pilot detects the target with a given probability will be less than the detection range of the observer. Conversely, the probability of detection by the observer at a given range will be higher than that of the pilot. Consider the case in which the size of the sector searched by the observer is the same as that of the search subsector for the pilot (this is an unlikely situation but will serve for purposes of illustration) so that the integrands of the two equations are equal. P_p will be less than P_o because τ is greater than T. The two probabilities can only be equal if τ is equal to $2mT$. Refering to equation 4.2 it is seen that τ equals 2m T if t is zero and k is one. In practical terms this is equivelent to saying that the pilot spends no time in the operation of his aircraft or he is acting exactly like an observer.

The method for computing the probability of pilot detection of a target follows that outlined in Chapter III. The required inputs are the same as those for the observer case with the following variations:

1. Azimuthal angle - Θ, and elevation angle - Φ will be

larger than for the observer since the pilot has no prior knowledge of the existence of a target.

2. The length of the time of one glimpse - T includes the dead time spent scanning to the position of the next glimpse.

Additional values are required for:

1. The number of glimpse sequences occuring in one search cycle - m .

2. The length of time which the pilot spends in the operation of his aircraft during a search cycle - t .

3. The number of sub-sectors into which the field of view is divided - k.

A numerical example of the calculation of detection probabilities for the pilot and the observer is presented in Appendix II for a specified set of input conditions.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Section A: Conclusions

The cumulative probability of detection by the observer or the pilot is controlled by three factors:

1. Relative closing velocity of the target.
2. Time spent searching a given location for the target.
3. Size of the area being searched.

The individual effect of each of these quantities is discussed in Appendix I, but, in general, reduction of any of these values will lead to a higher probability of detection.

Relative closing velocity is a physical fact of the problem and, therefore, not under the control or influence of the searcher. Physiological studies of the human eye indicate that there is a lower limit of about 1.5 seconds required for the eye to establish a definition of a target. Eye training methods may afford the individual the ability to develop glimpsing procedures which consistently approach this limit for glimpse times. It does not appear, however, that either of these areas offer real promise for material and reliable improvement of visual detection probability.

On the other hand, reduction of the area which must be searched can be accomplished by the introduction of electronic aids such as radar or infrared sensors. The availability of an electronic aid: first, alerts the pilot to the presence of a potential collision target; and secondly, gives him the bearing of this target around which he may concentrate his visual search. This effectively changes the searcher's status from an unalerted pilot to that of the alerted observer: the two situations considered in this thesis. It will be seen that for the conditions of the

numerical example given in Appendix II, this means an increase by a factor of from 2 to 4 in the range at which the visual detection will be made with a given probability.

The attention of the reader is invited to the assumption of the model which places a uniform distribution on the glimpses occuring throughout the search sector. This distribution has certain desirable mathematical properties which permit the development of a relatively simple closed form for the detection equation. The experimental evidence supporting and rejecting this assumption is both limited and inconclusive. If contrary results become predominant, the detection equations must be modified to reflect more accurately the true state of the detection process.

Section B: Recommendations

The conduct of operational experiments under controlled conditions by which the validity of the detection equations could be tested is not only difficult due to the vagaries of atmospheric conditions but, also, offers some element of danger to the participants. It is felt that use of a modified flight simulator with a panoramic screen such as is being developed by the Federal Aviation Agency can provide satisfactory comparative data.

The procedure of actually calculating the probabilities of detection by hand methods, as was done for the example in Appendix II, is not especially difficult but is long and tedious. At each step a separate determination is required for every range value used in the interval from zero to maximum detectable range. The integrands of the exponential term of the detection equations can not be directly integrated. Their values must be found either by numerical methods or by graphic methods with a mechanical integrator. The computational procedure can and should be programmed for solution by a

digital computer. This would allow a sensitivity analysis to be conducted of the input parameters and a clearer insite into the effect of these parameters on the probability of detection.

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APPENDIX I

Discussion of the Variables of the Detection Equation

The chance or probability of a detection in a single glimpse was stated in equation 3.3 as the ratio of the detection lobe solid angle to the solid angle of the search sector.

$$G = \theta^2/(\Theta+\theta)(\Phi+\theta) \qquad 3.3$$

Clearly the smaller the angles of Θ and Φ the larger the value of G. If the whole sky must be searched, the chance of seeing the target in a single fixation is quite small. If on the other hand, there is more than one person available to conduct the search or advance information is acquired as to the general position of the target, the size of the search sector for an individual can be reduced and the probability of detection is increased.

G is only one of the variables which effects the probability of detection as given in the general equation:

$$P\ (R) = 1 - EXP \left[1/VT \int_{R}^{R_m} LN\ (1 - G)\,dR \right] \qquad 3.8$$

First consider the integrand LN (1 - G). Since (1 - G) is always less than unity, the integrand is always negative. The smaller the value of (1 - G) the greater is the negative value of the integrand; thus, the smaller the whole exponential term and the greater the probability of detection. This is a reasonable result to expect since a large value of G means a greater chance of detection in one glimpse and should, therefore, produce a corresponding larger value of P(R).

Next consider the influence of the glimpse time T on the probability of detection P(R). Since it is in the denominator of the exponential, the smaller it is the greater is the value of the negative exponent and again

the greater the value of P(R). This makes physical sense since the smaller T, the greater the number of glimpses that can be made while the target is closing to some point R. T does, however, have a lower limit determined by the minimum number of fixations required during a glimpse to establish a definition of the target (see Section D of Chapter I).

Finally, the relative target velocity V also enters in the denominator of the exponent and thus has exactly the same effect as T. For a smaller V, the greater is the time taken by the target in closing to any range R. This greater time allows the observer to make a greater number of glimpses and increase the probability of detection.

APPENDIX II

Numerical Example of Computation

This appendix presents a numerical example of the results which are obtained for a given set of inputs when the probability of detection by the observer and the unalerted pilot are computed. So that the reader may more easily visualize the relative magnitude of the results obtained, the meteorological conditions, contrast, target size and speed, and search aircraft speed and configuration are kept the same for both computations. In effect, this simulates a situation in which the observer and the pilot are riding in the search aircraft at the same time. A comparison of the resulting probabilities of detection allows one to see the effect of size of the search area and search time on the individual's chance of making a detection.

The previously stated assumptions of the model are that the two aircraft are operating during daylight conditions in routine level flight on courses and at speeds such that a collision or near-collision will result. The atmospheric conditions are such that a uniform background of horizon sky is present.

For classification reasons as well as mathematical simplicity the search and target aircraft were both selected to be of the DC-3 type traveling at the same speed.

The following parameters which are common to both detection equations were selected as inputs:

1. Inherent contrast - $C_o = 0.5$.
2. Meteorological range - $v = 25$ nautical miles.
3. Maximum range at which a target can be detected based upon meteorological range and inherent contrast - $R_m = 14$ nautical miles.

4. Velocity of the search aircraft - S_s = 150 knots, and velocity of the target aircraft - S_t = 150 knots.

5. Frontal area - A_f = 72 Sq. Ft., and side area - A_s = 720 Sq. Ft., of the target.

Values of apparent contrast are computed for convenient range intervals from R_m to zero from equation 2.4

$$C_R = C_o e^{-3.912\, R/v} \tag{2.4}$$

It will be recalled that Figure 1 represents the results of Blackwell's study of the relation of apparent contrast and threshold target diameter under daylight conditions. Using the computed values of C_R above the corresponding threshold target diameters, α_ℓ, are determined.

From each triplicate of values (R, C_R, α_ℓ), a value of the angular distance in degrees from the threshold target center to the center of the fovea, θ, is found from:

$$C_R = 1.75\theta^{1/2} + \frac{19\theta}{\alpha_\ell^2} \tag{2.5}$$

Plotting θ against relative threshold target diameter, the threshold detection lobe pattern may be presented in rectangular form as shown in Figure 4.

The detection lobe found in this manner gives the minimum size target which will be detected at a stated angle off the foveal axis under the assumed meteorological conditions and target contrast. It is desired to compare this theoretical target size, which is a function of range, with the equivalent circular diameter of the actual target as a function of range. From the ratio of these two values, Figure 4 is entered to find the angle off the visual axis at which the actual target will be seen.

For the target and the search aircraft traveling at 150 knots, the arc of possible positions relative to the heading of the search aircraft from which the target must appear is found to be about 85 degrees to the left and right of that heading. The arguments of symmetry allow consideration of either half of this arc. Representative bearings of 80, 60, 30, 10, and 0 degrees relative in the left half of the arc were selected. The relative motion triangle is solved at each of these bearings on a standard Navy maneuvering board and values are found for the corresponding aspect angle, β , and relative closing velocity V.

Apparent target area may then be computed from:

$$A = A_f \cos\beta + A_s \sin\beta \qquad 3.2$$

And its equivelent circular diameter in minutes of arc from:

$$\alpha_t = 1293 \, A^{1/2} / R \qquad 3.1$$

The actual target diameter may now be compared with the theoretical target diameter. If the ratio α_f / α_t is greater than 1 the actual target will not be detected. For ratios less than one, Figure 4 is entered to find the angle off the foveal axis, θ , at which this target will be seen as a function of range.

Up to this point the computational procedure for both pilot and observer detection probability are exactly the same. One of the quantities necessary to find the probability of a detection in one glimpse has been found. The chance of a detection in one glimpse is:

$$G = \theta^2 / (\theta + \theta)(\Phi + \theta) \qquad 3.3$$

As can be seen from the above equation, there remains to be given the dimensions of the search sector for the observer and the determination of the search sub-sector for the pilot. With these values one may find the single glimpse probability. The cumulative probability of detection is determined with the additional inputs of glimpse time, T, for the observer and search cycle time, τ, for the pilot.

It should be borne in mind that a different value of θ will be found for each of the five representative target positions selected because θ will vary with target aspect. Also, due to symmetry, the cumulative probability of detection curves that result will give values for ten points within the 170 degree arc of possible positions from which the target may appear.

For the observer it was assumed that he had some prior information as to the approximate position from which the target would appear. This assumption has the effect of allowing a reduction in the size of the search sector to dimensions less than that of the general field of view. The axis of this search sector is considered to be directed at the relative bearing for which the target aspect angle was found. Since this observer expects the target to appear within this sector, he will more completely inspect each position in detail and thus have a longer glimpse time than that which is associated with routine search. The following input parameters were selected for the observer:

1. Azimuthal angle - $\theta = 4°$, elevation angle - $\Phi = 4°$.
2. Glimpse time - T = 3 seconds.

The necessary values of G are then found using equation 3.3. All the inputs to the cumulative probability of detection equation (3.8) are now available.

$$P_o(R) = 1 - EXP \left[1/VT \int_R^{R_m} LN\ (1 - G)\,dR \right] \qquad 3.8$$

The computations as a function of range have been completed for each of the five selected bearing and are shown on Figures II-1(a) through II-1(e).

The search aircraft selected for this example was a DC-3. This aircraft will have both a copilot and a pilot in the cockpit. The total field of view from this cockpit is limited in azimuth to about 100 degrees to either side by its configuration. It will be assumed that the pilot will be responsible for visual search in the left half of this field and the copilot for the right half. To simplify the computations and again make use of symmetry, it will be further assumed that the division of time for visual search and in cockpit duties is the same for either individual.

The field of view of the pilot is thus confined to an arc of 100° in azimuth. In Chapter 4 the azimuthal scan angle, Ψ , was defined as the angular distance through which the eye was trained between glimpses. Selecting 20° as the value of Ψ, the horizontal field of view is divided into 5 equal subsectors.

The pilot, who is conducting a general visual search and is unaware of the existence of a target, will cover a greater field of view in both azimuth and elevation than the observer, but the time spent in any one glimpse will be relatively small so that coverage of the whole field may be thoroughly but expeditiously accomplished. Input parameters reflecting these conditions were selected as follows:

1. Azimuthal angle - Θ = 9°, elevation angle - Φ = 9°.
2. Length of time of one glimpse including dead time of scanning - T = 1.5 seconds.

3. Number of sub-sectors into which the field of view is divided - $k = 5$.

4. Number of glimpse sequences occuring in one search cycle - $m = 1$.

5. Length of time which the pilot spends in the operation of his aircraft during a search cycle - $t = 15$ seconds.

The elapsed time in one search cycle is found from:

$$\tau = 2mk\ T + t \qquad 4.2$$

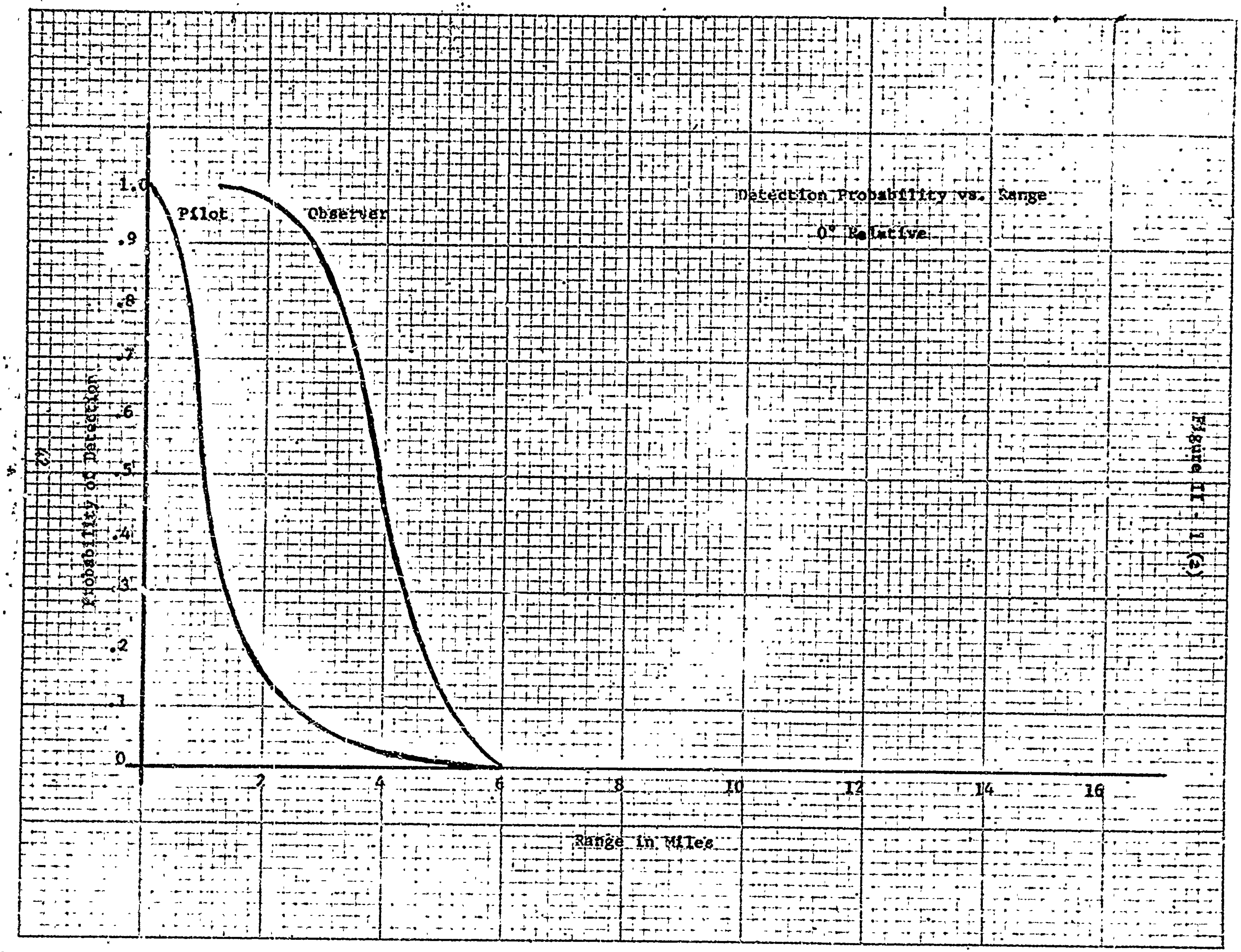
The required values are thus available with which to compute the cumulative probability of detection by the unalerted pilot as a function of range from equation 4.6.

$$P_p(R) = 1 - EXP\left[2m / V\tau \int_{R}^{R_m} LN\ (1 - G)\ dR \right] \qquad 4.6$$

The detection curves for the five selected bearings of target position are shown on Figures II-a(a) through II-1(e).

From these curves a polar plot may be constructed showing the range at which this target will be detected with a constant probability. Figure II-2 shows the case for a detection probability of Ø.5.

Figure II - 1 (2)



Detection Probability vs. Range
0° Relative
Pilot
Observer
Probability of Detection
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
2
4
6
8
10
12
14
16
Range in Miles

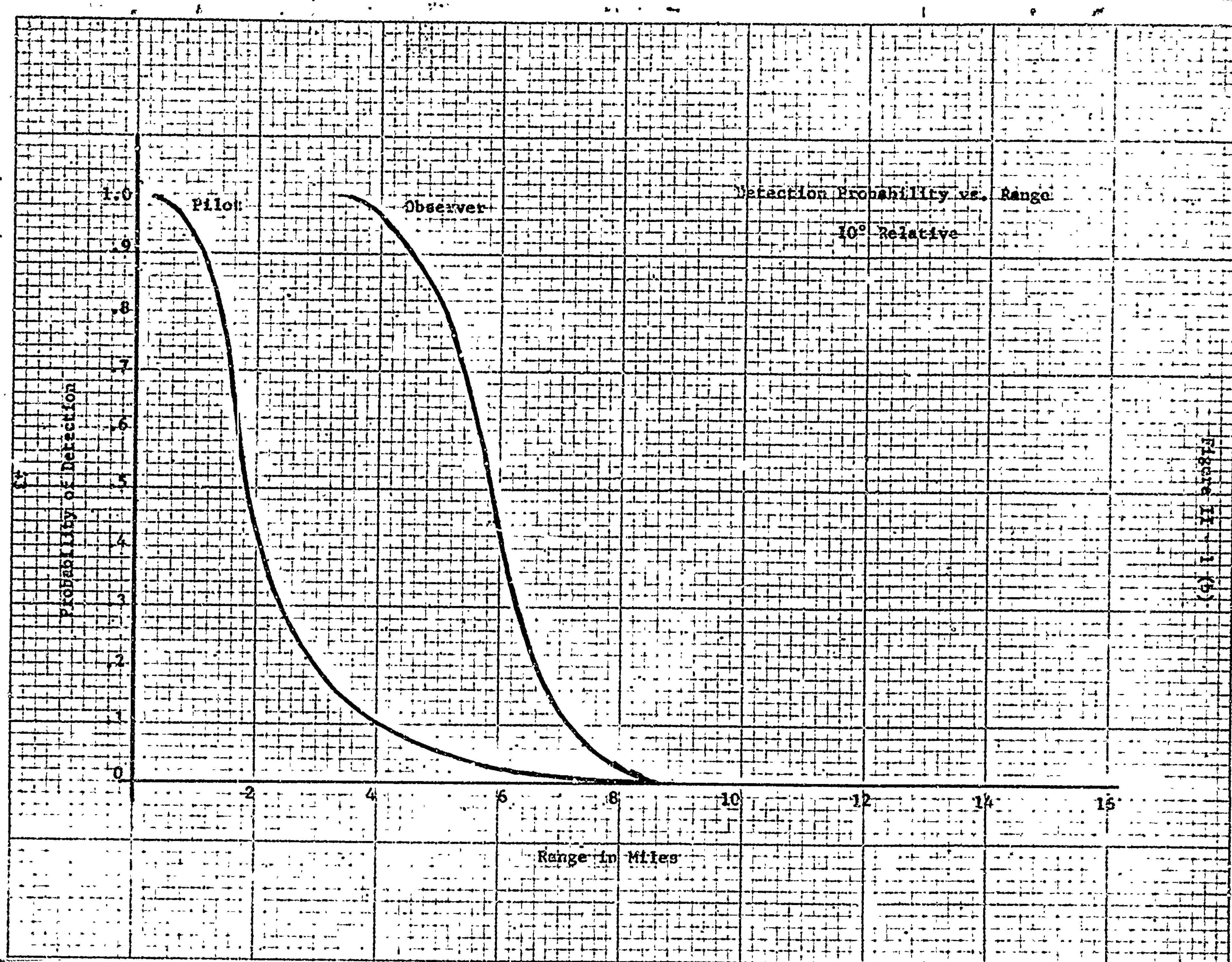
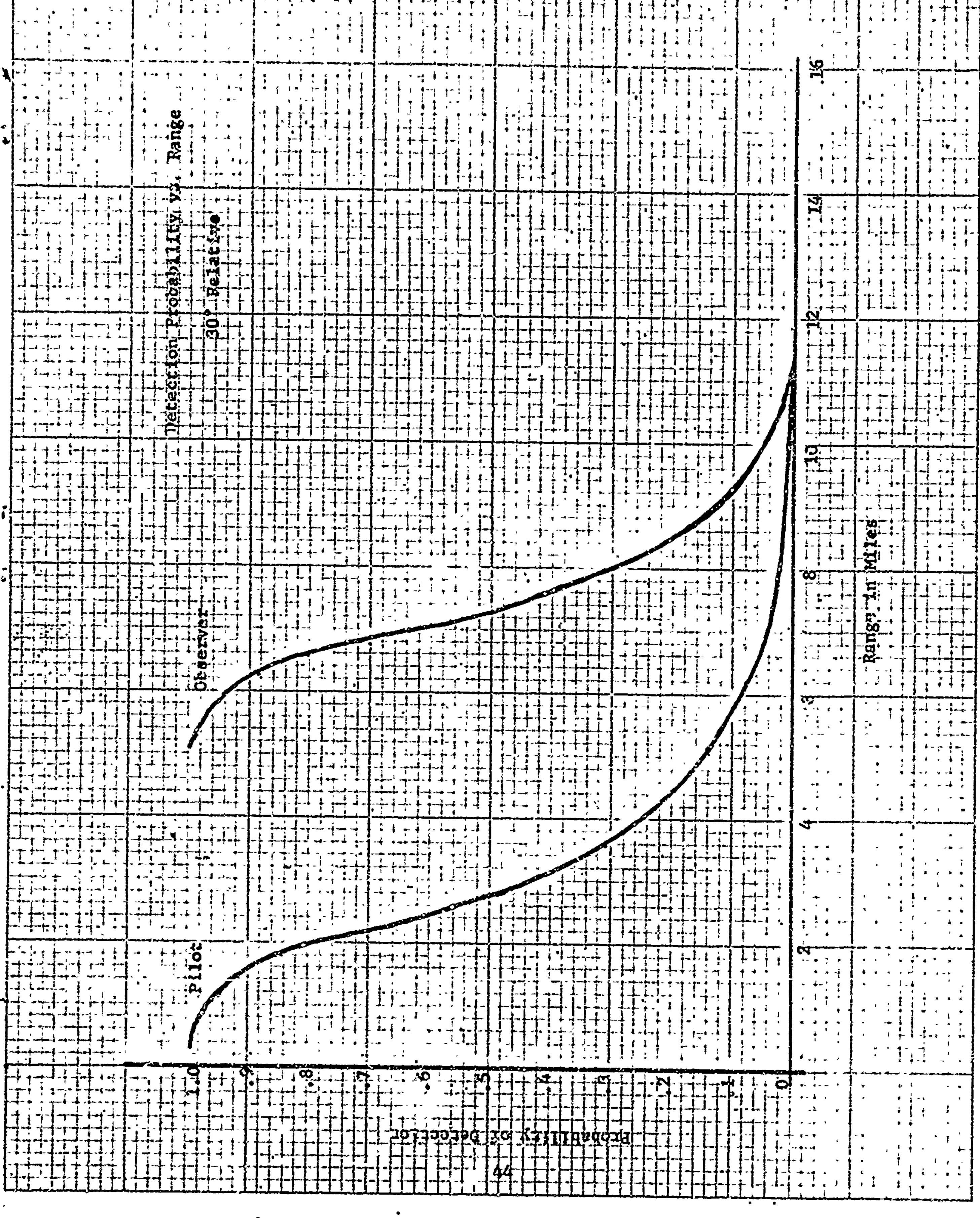

Detection Probability vs. Range
10° Relative
Pilot
Observer
Probability of Detection
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
2
4
6
8
10
12
14
15
Range in Miles

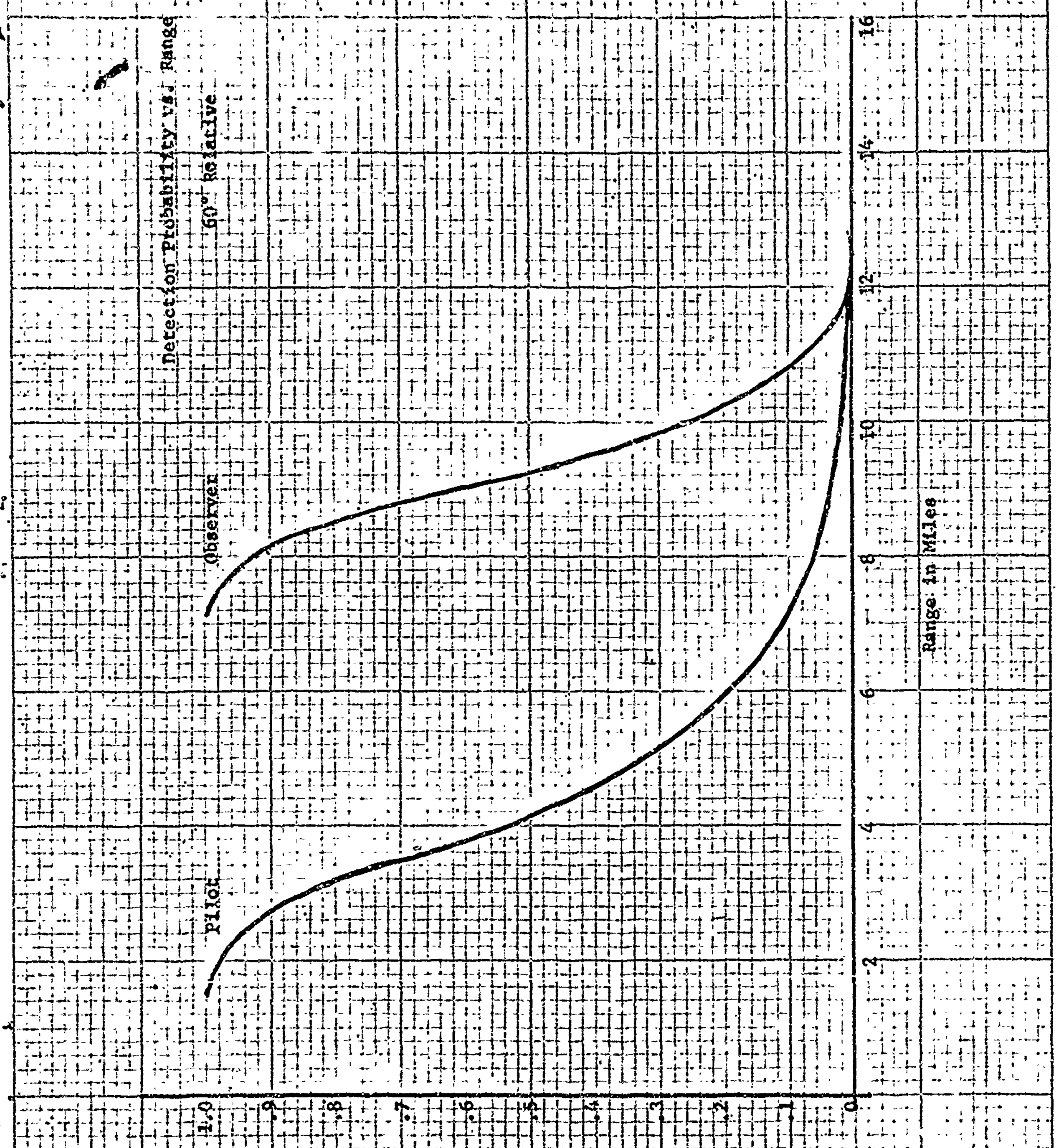
Figure II - 1 (b)

Figure II - 1 (c)



Detection Probability vs. Range
30° Relative
Observer
Pilot
Range in Miles
2
4
6
8
10
12
14
16
Probability of Detection
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0

Figure II - 1 (d)


Detection Probability vs. Range
60° Relative
Observer
Pilot
Range in Miles
2
4
6
8
10
12
14
16
Probability of Detection
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0

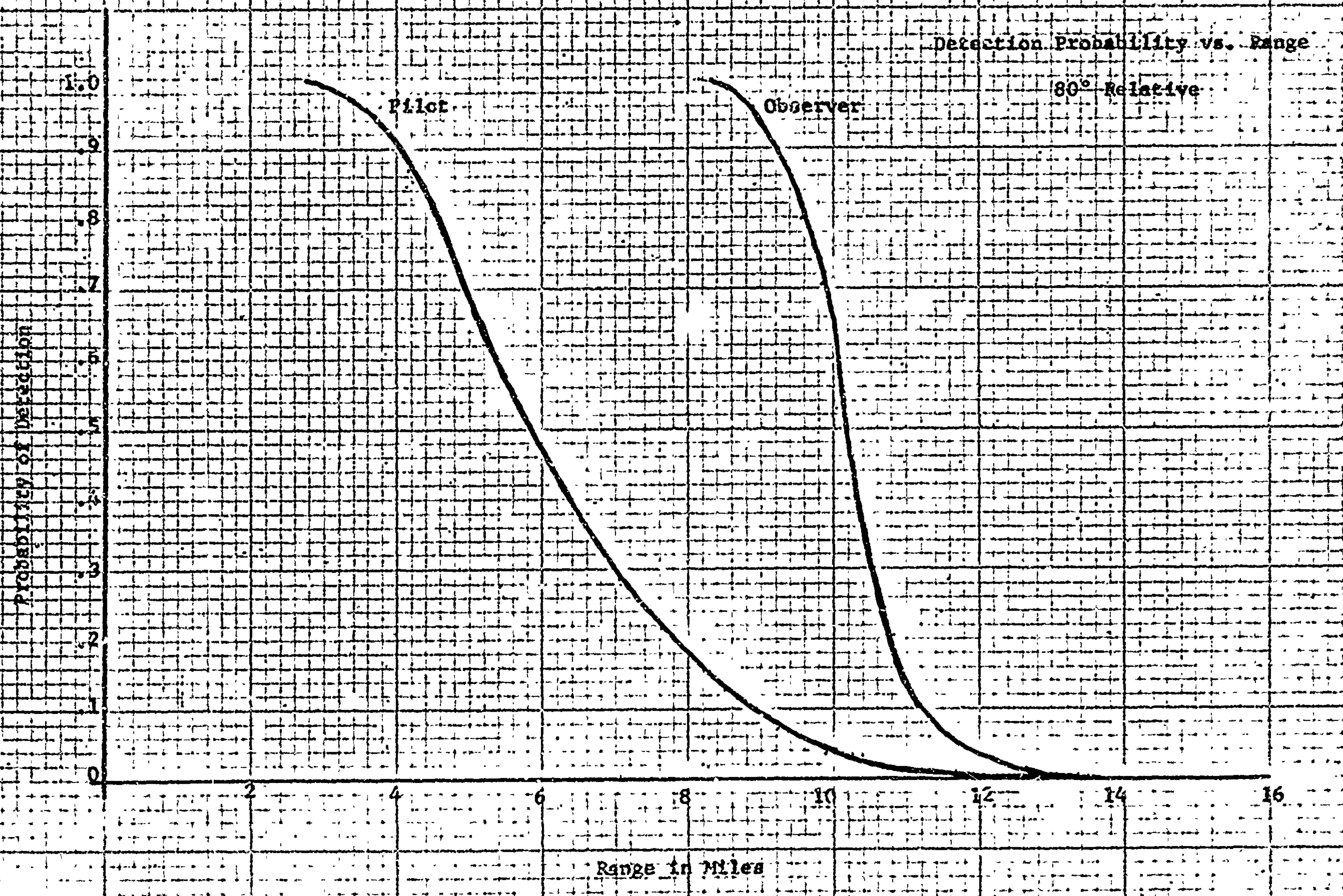
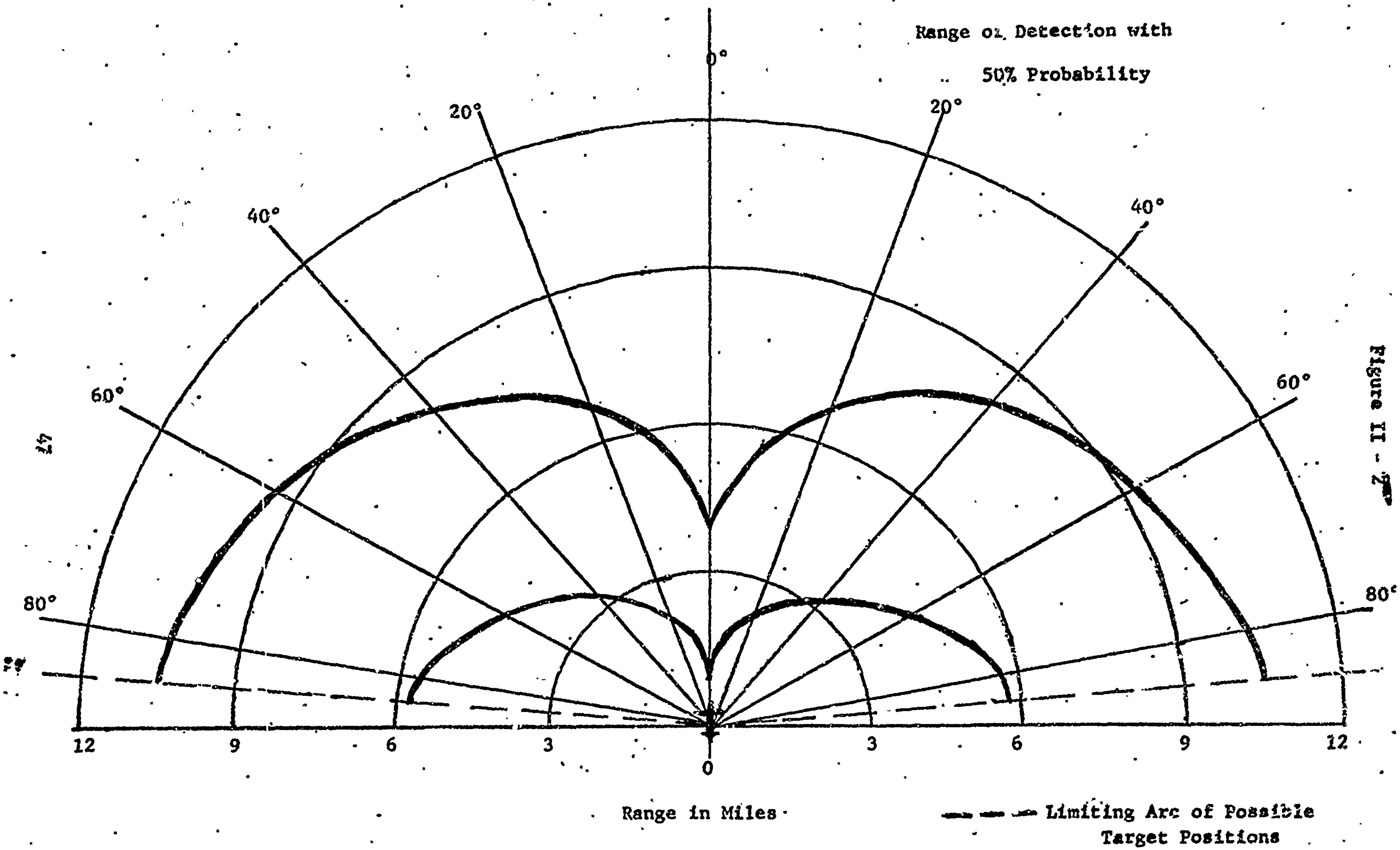

Detection Probability vs. Range
80° Relative
Pilot
Observer
Probability of Detection
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
2
4
6
8
10
12
14
16
Range in Miles

Figure II - 1 (e)



Range of Detection with
50% Probability
0°
20°
20°
40°
40°
60°
60°
80°
80°
12
9
6
3
0
3
6
9
12
Range in Miles
Limiting Arc of Possible
Target Positions

Figure II - 2